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Assessment of active landslides using field electrical measurements

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ABSTRACT

Landslide characterization and hazard assessments require multidisciplinary approaches that connect geologic processes with geotechnical parameters. Preexisting landslide activity, geology and geomorphology, soil strength, and hydrologic conditions are complex factors that affect landslide behavior. Often, the connections among these factors are not made for hazard assessments, forecasting, or slope stability modeling. Therefore, geophysical and geotechnical techniques for landslide investigations are typically assessed independently. This study aims to bring together different techniques to develop a methodology that connects electrical measurements and shear strength. A framework has been developed for using electrical resistivity measurements that will support and facilitate the prediction of shear strength within a slope. In-situ volumetric water content, soil-water potential (suction), and electrical conductivity were measured from two shallow colluvial landslides in Kentucky. Repeated surface electrical resistivity survey measurements were used to characterize the failure zone and lithology, and to compare with the in-situ hydrologic measurements. The data show that subsurface moisture conditions over time can be reflected in the inversions of repeated ER surveys, thus allowing electrical measurements and geotechnical parameters to be correlated. This study demonstrates that electrical resistivity can be used as a tool for landslide monitoring and to assess shear strength. These parameters are pertinent to investigating the stability of landslides that are often triggered or reactivated by rainfall.

1. Introduction

Landslides pose serious threats to highways and transportation infrastructure, homes, industrial structures, and utilities. The U.S. Geological Survey estimates that landslides cause in excess of $1 billion in damage and about 25 to 50 deaths each year in the United States, and worldwide they are responsible for thousands of fatalities and hundreds of billions of dollars in damage. In Kentucky, direct costs resulting from landslide mitigation along roadways and requests for Kentucky Emergency Management Hazard Mitigation grants for landslide-damaged homes are estimated to exceed $10 million per year (Crawford, 2014; Overfield et al., 2015). Assessment of mechanisms leading to failure greatly increases the capacity to model and predict future occurrences of these hazards.

Geophysical methods such as electrical resistivity (ER) are commonly used in hydrologic and geotechnical investigations for subsurface characterization. The geophysical properties of a soil system are affected by parameters such as soil type, pore structure, degree of saturation, stress state, and history. These parameters also affect the strength and deformation behavior of a soil system. Thus, there is a high likelihood that geophysical measurements in soil systems will provide a reliable means to evaluate and predict engineering behavior. In addition, geophysics-based monitoring systems can be field-deployed at costs less than that of traditional geotechnical monitoring systems. Several researchers (Lapenna et al., 2005; Mahmut et al., 2006; Perrone et al., 2008; de Bari et al., 2011; Travelletti et al., 2012; Perrone et al., 2014; Crawford et al., 2015) have used geophysical techniques such as electrical resistivity tomography (ERT) to define landslide morphology, depth-to-slide plane, lithologic interfaces, and moisture regimes. ERT is a two- or three-dimensional image of spatially distributed ER data. The advantage of ERT data is that they allow variations in moisture content and geologic materials to be determined over a large volume directly involved with the landslide, rather than at a single discrete point. Clearly, correlating ER data with strength data would be a significant benefit.

Using geotechnical data alone for landslide assessment will provide detailed information at only discrete locations. Natural geologic formations are typically highly variable spatially, however. Geophysical data can provide bulk spatial data for a site, but most geophysical data do not provide detailed information regarding the shear strength or the engineering behavior of the soil. The optimal solution to this dilemma is to couple the geophysical and geotechnical data using laboratory-based

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models that account for the geologic conditions at a particular site and that directly and indirectly relate geophysical measures to geotechnical parameters and behavior. The purpose of this study was to develop a framework that uses field and laboratory techniques to correlate in-situ hydrologic data and surface ER data to predict shear strength. An assessment of the hydrologic behavior in two shallow colluvial landslides supports the use of ER as a tool to characterize landslide structure and soil shear strength.

2. Background

Landslide behavior and stability, especially for shallow colluvial landslides, are highly influenced by fluctuating water content and stresses in the unsaturated zone. These factors also contribute to subsequent landslides (Godt et al., 2009, 2012; Bittelli et al., 2012; Lu and Godt, 2013). Stresses in the unsaturated zone vary because of transient water flow, perched water, and soil characteristics. Shear strength of the soil system is the mobilized shear stress along a failure plane at failure. In-situ soil systems are partially saturated and exhibit fluctuations in matric suction (water potential), which is the difference between the pore air pressure and the porewater pressure (i.e., $u_a - u_w$) and fluctuations in effective stress. Matric suction and effective stress are often reduced when rainfall increases (Godt et al., 2009; Lu and Godt, 2013; Oh and Lu, 2015). Therefore, shear strength will also vary with moisture conditions.

Rainfall is a common landslide trigger, increasing the load and porewater pressures, and reducing shear strength. General relationships between varying soil moisture conditions and electrical data, and changes in soil strength are seldom demonstrated, however. Most investigations using field electrical data, such as ERT, for landslide assessment tend to focus on how ERT can be used to elucidate changes in soil moisture (Li et al., 2005; Travelletti et al., 2012; Bittelli et al., 2012; De Vita et al., 2012; Lehmann et al., 2013; Piegari and Di Maio, 2013). Other researchers (Cosenza et al., 2006; Sudha et al., 2009; Siddiqui and Osman, 2013) have attempted to ascertain soil properties pertinent to landslide assessment using field ER data. The aforementioned researchers did not present a comprehensive framework for relating field ER measurements with geotechnical behavior of a partially saturated soil system, subjected to seasonal variation in the moisture conditions, however.

This study establishes a methodology to determine the shear strength of soils from electrical data by comparing in-situ hydrologic parameters and electrical conductivity, along with surface electrical resistivity. The data were evaluated over multiple seasons to assess the effects of transient water fluctuations in shallow colluvial landslides. The results of this study were used to develop a framework of predictive stability models for slope systems. This baseline framework will ultimately inform engineering decisions, planning and development, safety decisions, and infrastructure resilience.

3. Field methodology

Two active landslides in Kentucky were the basis of this study. Each landslide occurs in a different geologic setting and has a different slope history. The landslides occur in relatively horizontally bedded clastic and carbonate sedimentary rocks draped with varying thicknesses of colluvium. The landslides are of different sizes, with different volumes of material and depths to failure. In addition to the variable geology, site permission, accessibility, and proximity to past landslide activity influenced which sites were chosen.

The Doe Run landslide is located in Erlanger, in northern Kentucky, just south of Cincinnati, Ohio, in the Outer Bluegrass physiographic region (McDowell, 1986). The geology of northern Kentucky and the Cincinnati area consists of interbedded shale (75 to 80%) and limestone (20 to 25%). Clay-rich colluvial soils of varying thickness cover steep slopes and result in high landslide occurrence (Haneberg, 1991).

The monitored slope is a thin translational landslide in which the slide plane occurs along the colluvial-bedrock contact. The colluvium thickness varies from a meter or less upslope to approximately 4 m near the toe. The headscarp and landslide flanks are difficult to observe, except in a small slump at the toe of the slope that exhibits these features well. The length of the downslope axis of the monitored area is approximately 52 m. Fig. 1 shows the location of the Doe Run landslide. In the figure, the black dashed line represents the slump downslope at

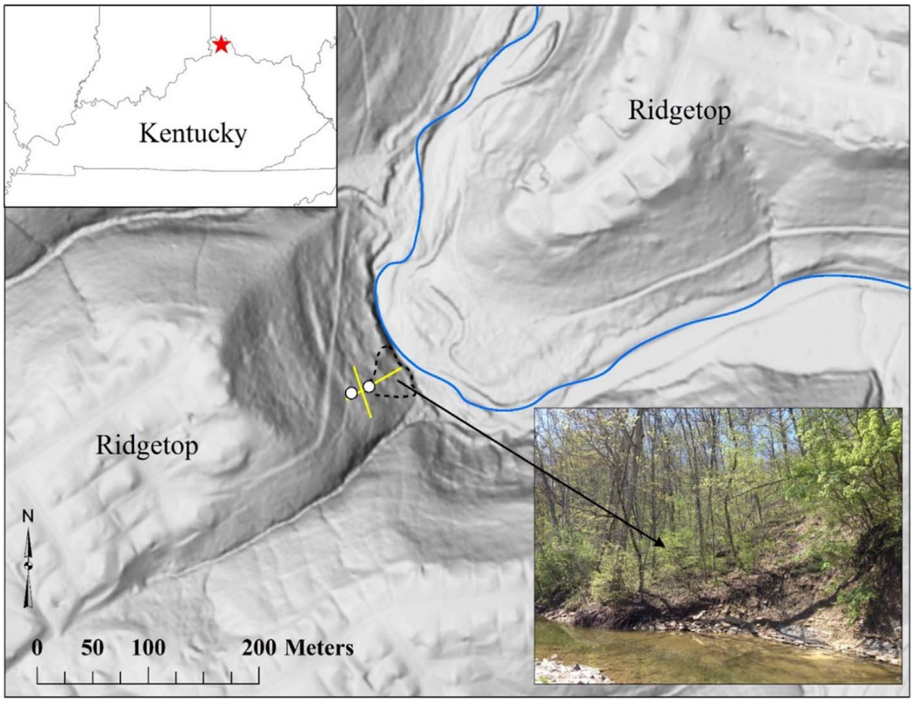

Fig. 1. Overview of the Doe Run landslide.